Investigation of anthropogenic aerosol effects on ice and mixed-phase clouds and associated precipitation based on satellite observations

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Status:

- ❑ Investigated the impact of aerosols on micro- and macro-physical properties of ice clouds.
- ❑ Elucidated the modulation of the aerosol impacts by meteorological conditions, aerosol type, and ice cloud type.

Objective:
This project will provide a comprehensive assessment of the impact of aerosols, especially anthropogenic aerosols, on properties of ice and mixed-phase clouds and the associated precipitation, using observations from multiple satellites, including MODIS, CALIPSO, and CloudSat.

Needed Products:

- MODIS, CALIPSO, CloudSat

Related Publications:

- Zhao, B.*, Y. Gu*, K. N. Liou, Y. Wang, X. Liu, L. Huang, J. H. Jiang, and H. Su, 2018: Type-dependent responses of ice cloud properties to aerosols from satellite retrievals. *Geophys. Res. Lett.*, **45**, 3297-3306, DOI 10.1002/2018GL077261 (*corresponding author).
- Zhao, B.*, K. N. Liou, Y. Gu*, J. Jiang, Q. Li, R. Fu, L. Huang, X. Liu, X. Shi, H. Su, and C. He, 2018: Impact of aerosols on ice crystal size. *Atmos Chem Phys,* ***18,*** *1065-1078,* DOI 10.5194/acp-18-1065-2018 (*corresponding author).

Type-dependent Aerosol Impact on Ice Clouds from Satellite Retrievals

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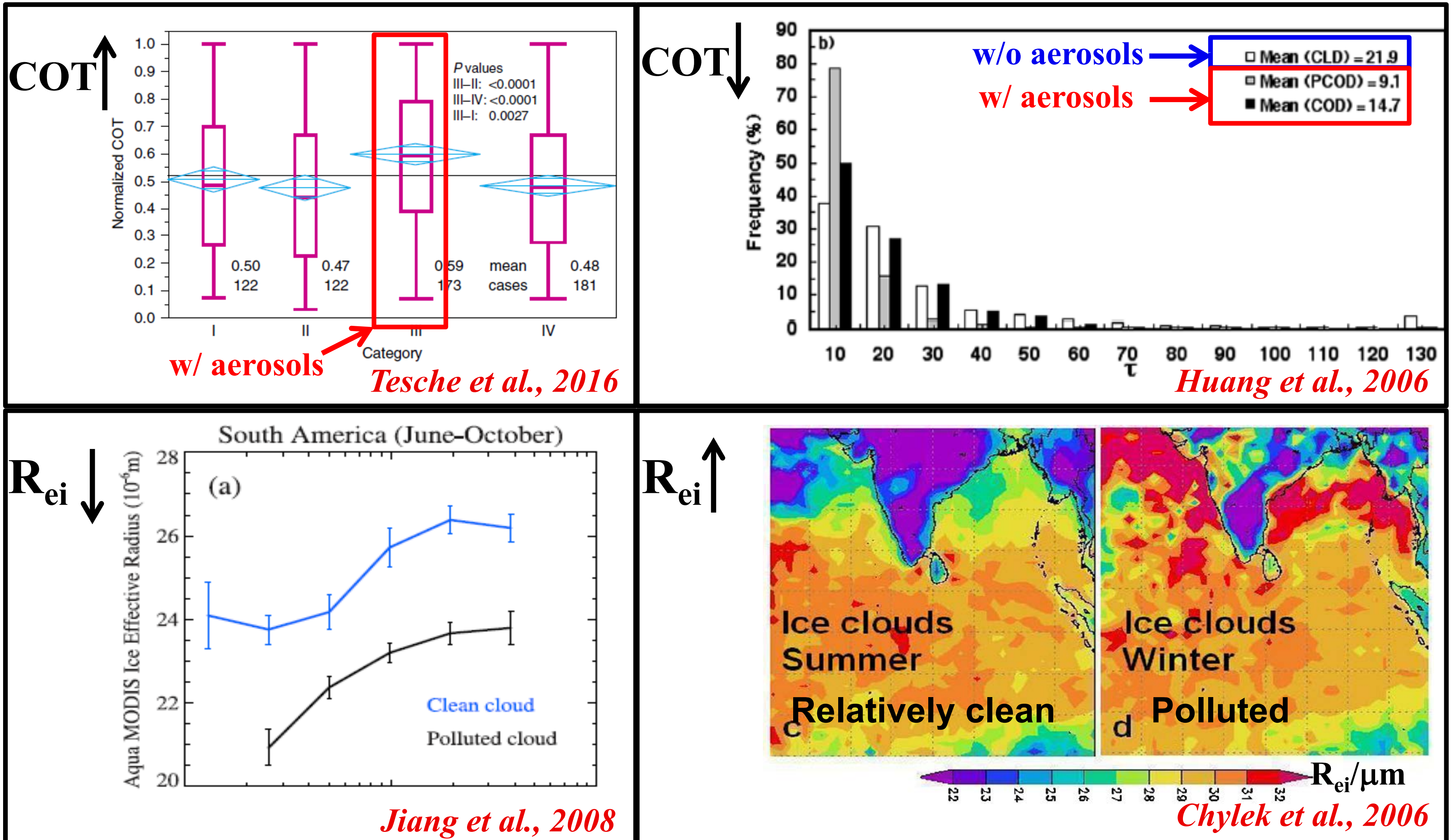
MODIS/VIIRS Science Team Meeting, 10/15/2018

Limited and conflicting observational evidence for the aerosol impact on ice clouds

- **Global aerosol-ice cloud radiative forcing: [-0.67, 0.70 W/m^2]**

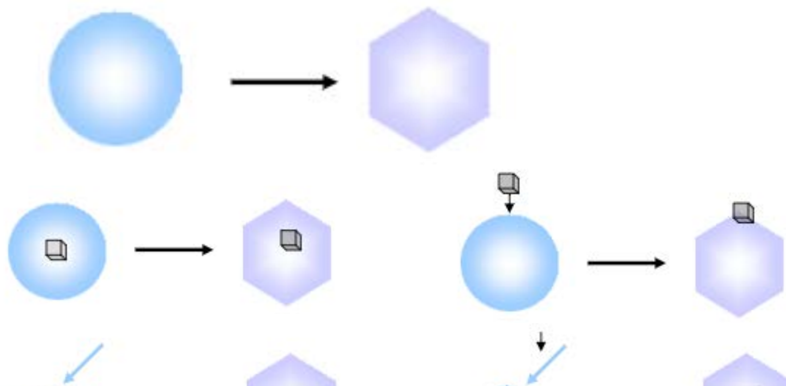
(Fan et al., 2016; IPCC, 2013; Liu et al., 2009)



Possible reasons for disagreement: aerosol and ice cloud types

Homogeneous nucleation

Heterogeneous nucleation

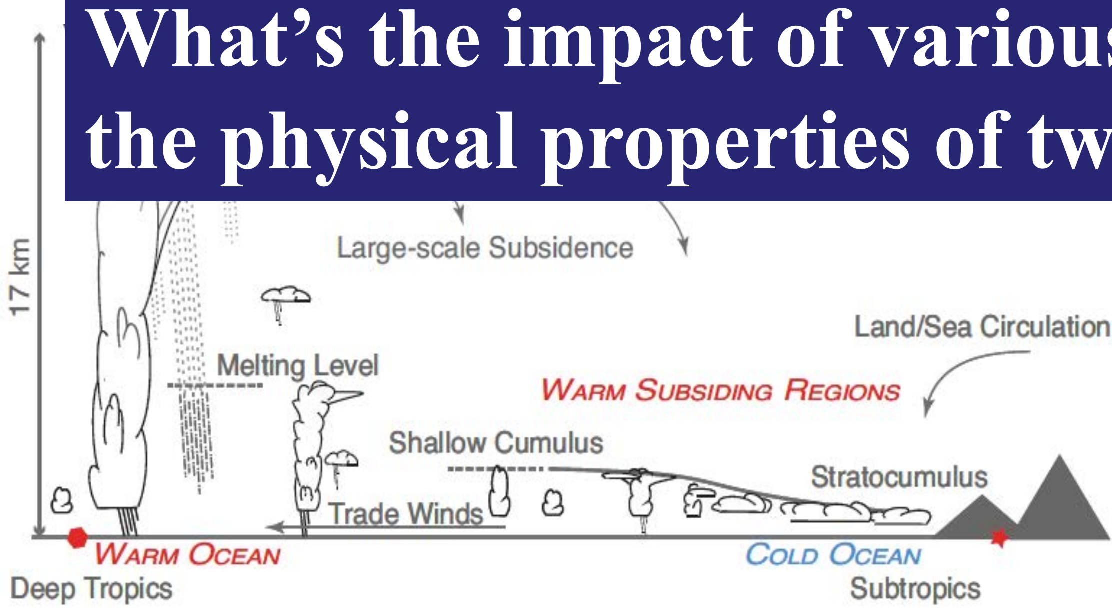


Most aerosol types

INP
- **Dust** √
- **Biological** √
- **BC** ?

Key scientific question:

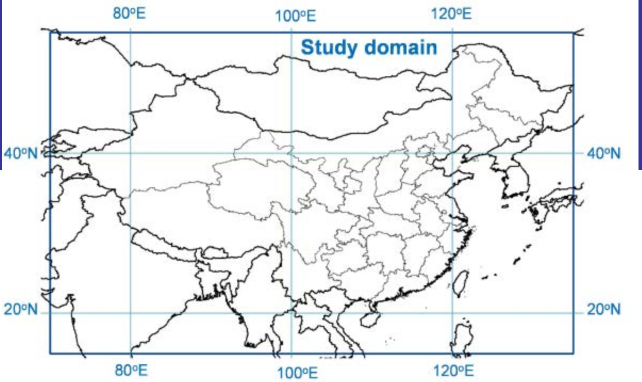
What's the impact of various aerosol types on the physical properties of two ice cloud types?



nonabsorbing aerosols

- ❑ **Convection-generated vs. in-situ formed ice clouds**

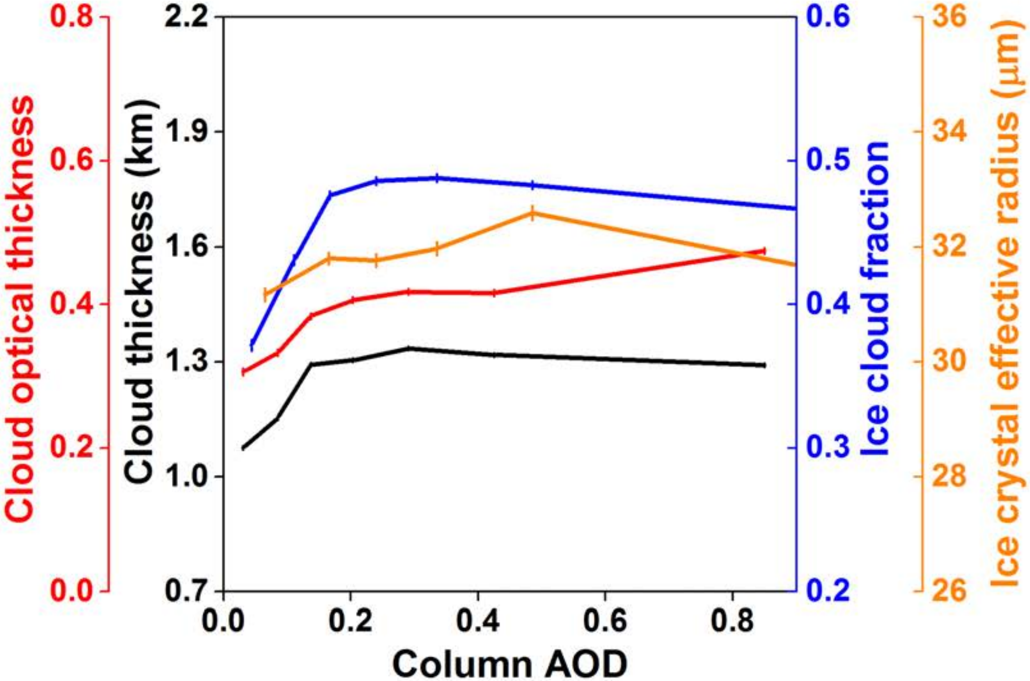
Sources of satellite data

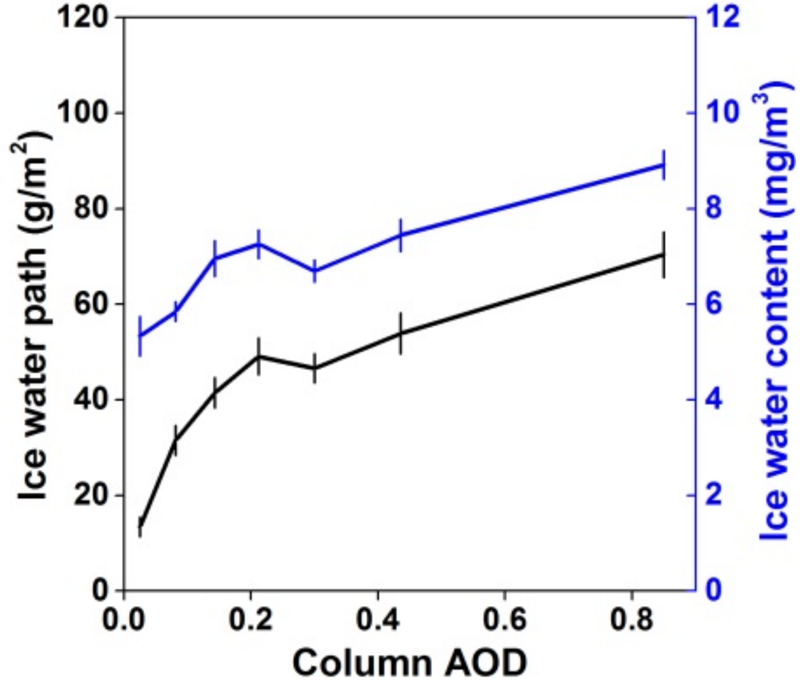


- Time period: 2007-2015 (9 years)
- Spatial coverage: East Asia (15º-55º N, 70º-135º E)

Satellite/ Sensor	Product	Variable
Aqua/ MODIS	MYD04 (Level 2, Collection 6)	AOD
	MYD06 (Level 2, Collection 6)	R_{ei}, ice cloud fraction (ICF), cloud phase, etc.
CALIPSO/ CALIOP	05kmMLay (Level 2, V4.10)	Aerosol/cloud layer number, feature classification flags, QA flags, cloud top/base height, layer base temperature, layer aerosol/cloud optical depth
	05kmAPro (Level 2, V 4.10)	Meteorological parameters
CloudSat/ CPR	2C-ICE (Level 2, Version P1_R04)	Ice water path (IWP), vertically resolved ice water content
--	NCEP ds083.2	Meteorological parameters

Overall changes in ice cloud properties with aerosols





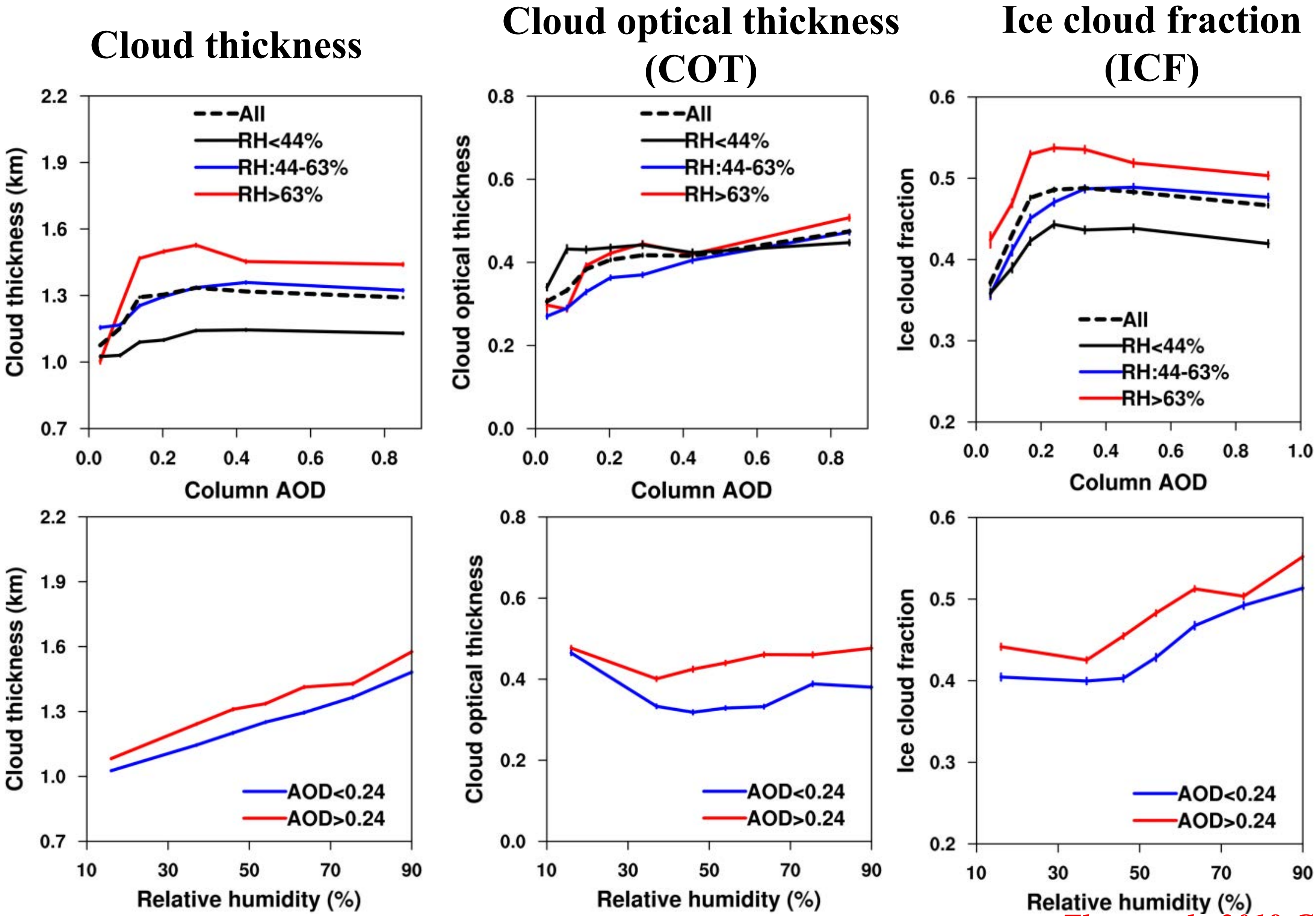
Zhao et al., 2018 ACP; 2018 GRL

- **Cloud thickness, COT, ice cloud fraction (ICF), ice water path (IWP), and ice water content (IWC) all increase rapidly with AOD < 0.3, and level off at higher AOD.**
- **R_{ei} increases with AOD < 0.5, and decreases slightly with further AOD increase.**
- **Exclude the impact of meteorological covariation and cloud contamination of aerosol retrievals.**

Aerosol effects or meteorological effects?

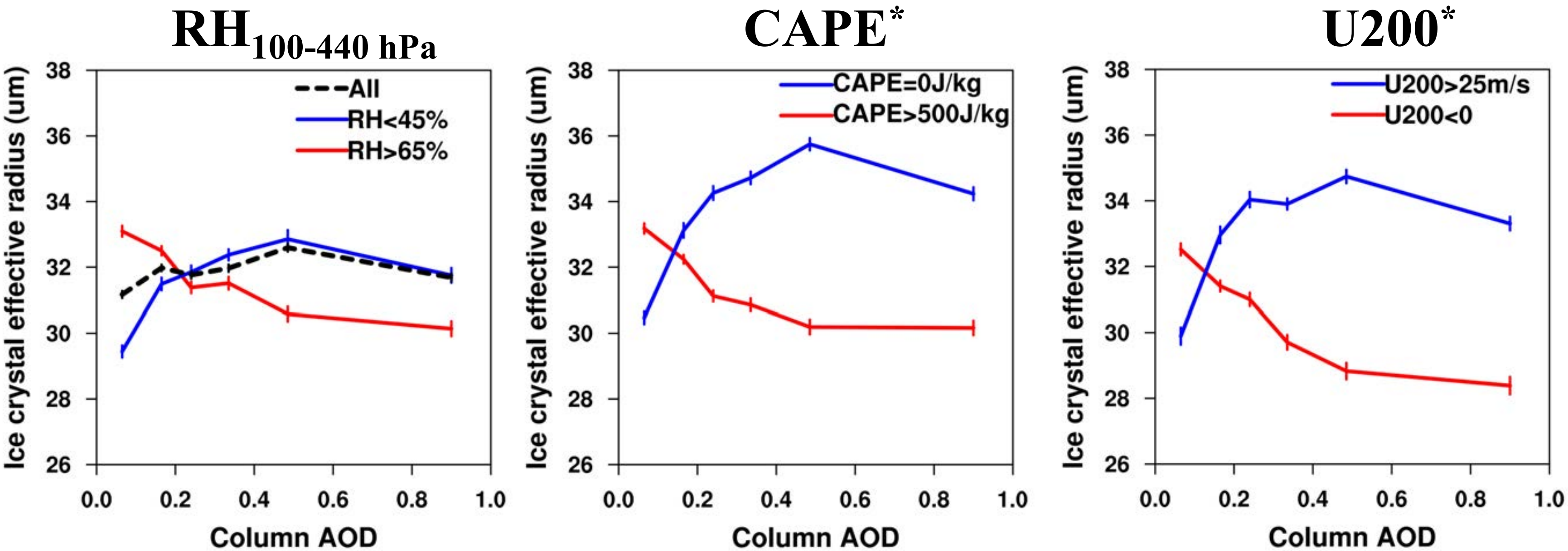
- **Meteorological parameters that can potentially affect ice cloud formation and evolution:**
  - **Relative humidity averaged between 100 and 440 hPa ($RH_{100-440hPa}$)**
  - **Convective available potential energy (CAPE): an indicator of convective strength**
  - **Middle cloud layer temperature**
  - **Wind speed and direction at ice cloud height and at surface**
  - **Vertical velocity below and at ice cloud height**
  - **Vertical wind shear.**

Aerosol effects or meteorological effects?



Zhao et al., 2018 GRL

R_{ei}-AOD relationships modulated by meteorology



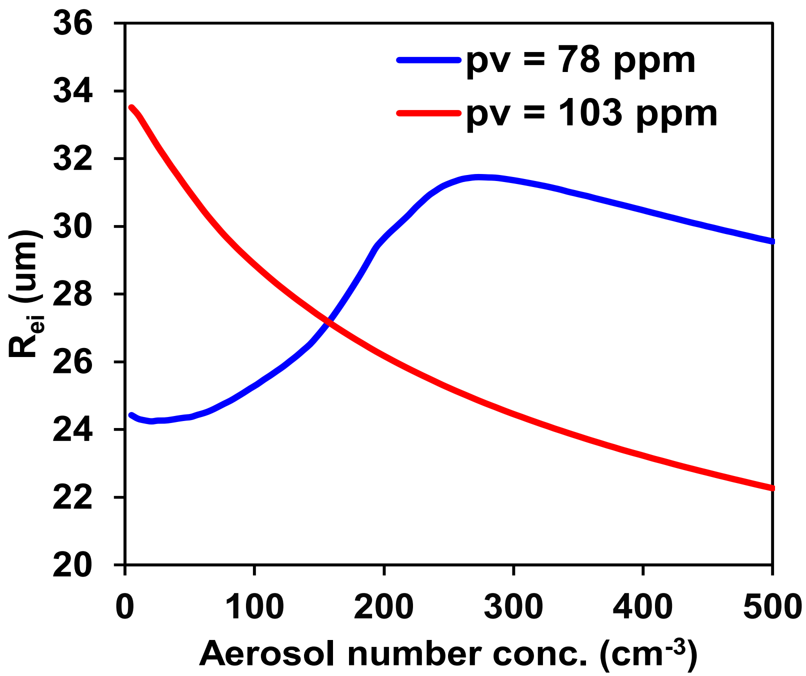
Zhao et al., 2018 ACP

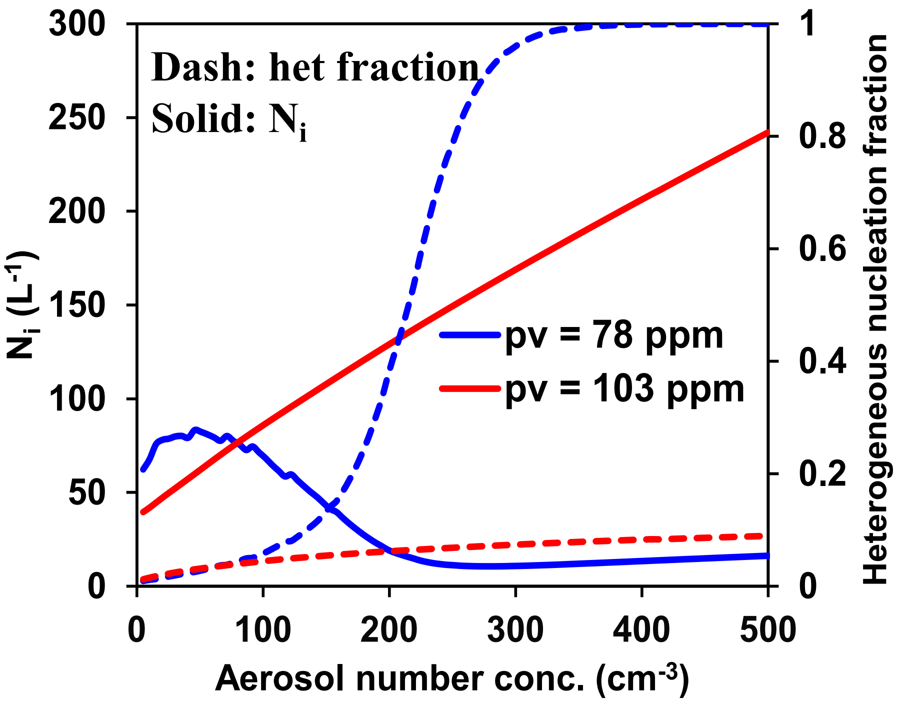
- **R_{ei} decreases significantly with increasing AOD for high-$RH_{100\text{-}440\ hPa}$/high-CAPE/negative-U200, consistent with the rule of "Twomey effect". In contrast, however, for low-$RH_{100\text{-}440\ hPa}$/low-CAPE/positive-U200, R_{ei} increases rapidly with AOD.**
- **Both the positive and negative correlations between R_{ei} and AOD are primarily attributed to the aerosol effect.**
- **$RH_{100\text{-}440hPa}$, CAPE, and U200 are all closely related to the amount of water vapor in the upper atmosphere.**

***CAPE: convective available potential energy**
U200: U-component of wind speed at 200 hPa

Modeling support for the water vapor modulation

- **Cloud parcel model simulation**
  - **Homogeneous nucleation** of sulfate solution droplets
  - **Deposition nucleation** on externally mixed dust (prescribed to be 0.0075% of sulfate)
  - **Immersion nucleation** of coated dust droplets (prescribed to be 0.0025% of sulfate)
  - **Other processes: depositional growth, sublimation, and sedimentation**
- **Finding: water vapor modulates the relative importance of different ice nucleation modes, leading to the opposite aerosol impacts between moist and dry conditions**



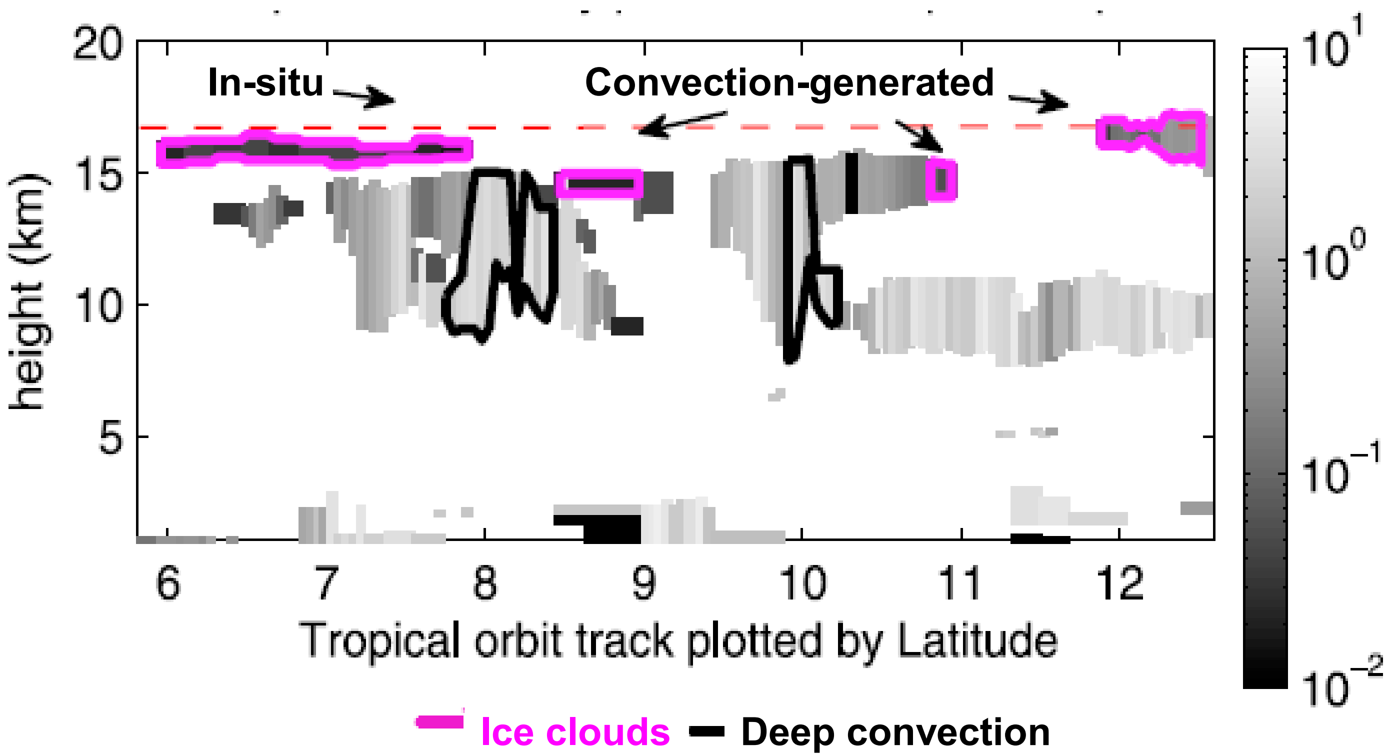


pv: initial water vapor mass mixing ratios

Zhao et al., 2018 ACP

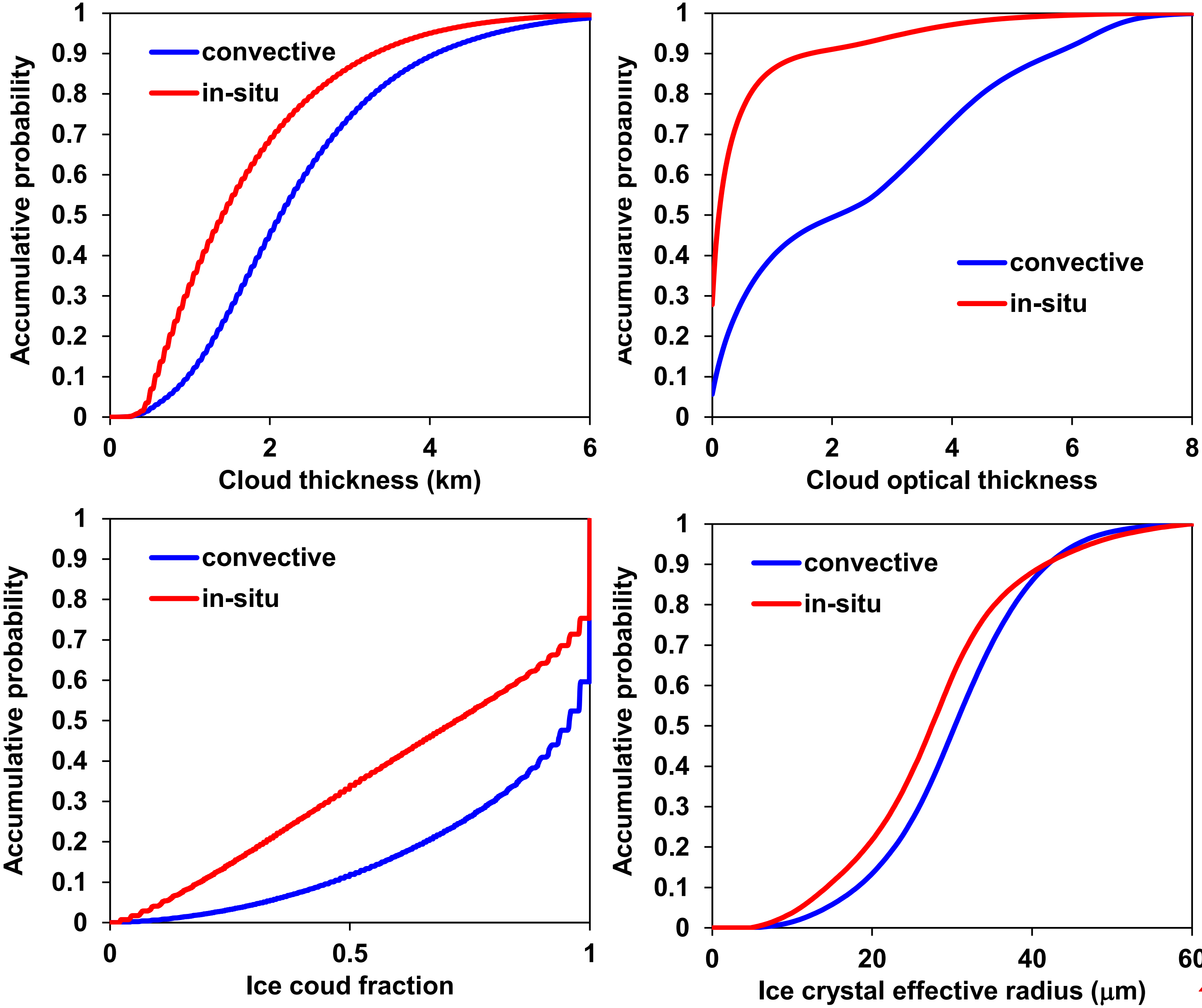
Classification of ice clouds using CALIPSO

- Classify ice clouds based on their connection to deep convective clouds
  - Convection-generated ice clouds: consist of ice cloud profiles that are directly connected to deep convective profiles.
  - In-situ ice clouds: at least 95% of the cloud consists of continuous ice cloud profiles which are at least 25 km in horizontal direction, and none of the remaining profiles are deep convection type.



Zhao et al., 2018 ACP; Riihimaki and McFarlane, 2010

Distribution of properties of two ice cloud types



Profile number:

<u>Convection-generated</u>

1407104 (51.1%)

<u>In-situ formed</u>

1269272 (46.1%)

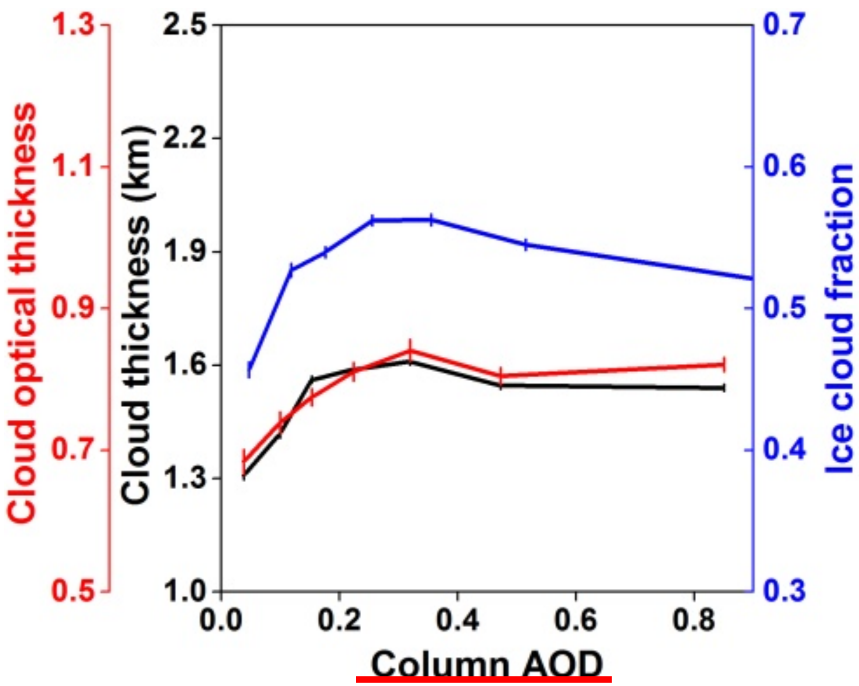
<u>Others</u>

75471 (2.7%)

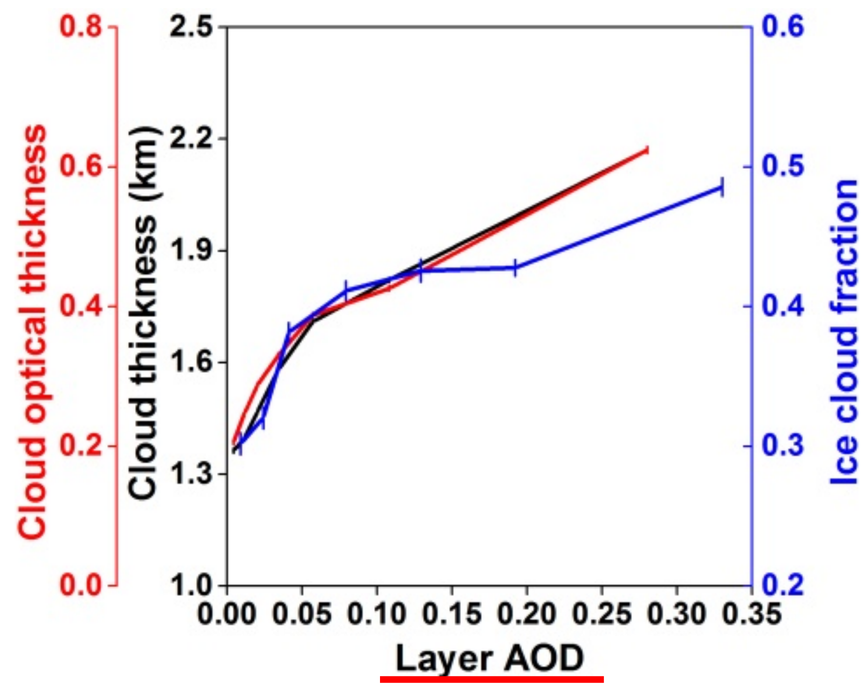
Zhao et al., 2018 ACP

Responses of properties of two ice cloud types to aerosol loading

Convection-generated ice clouds



In-situ formed ice clouds

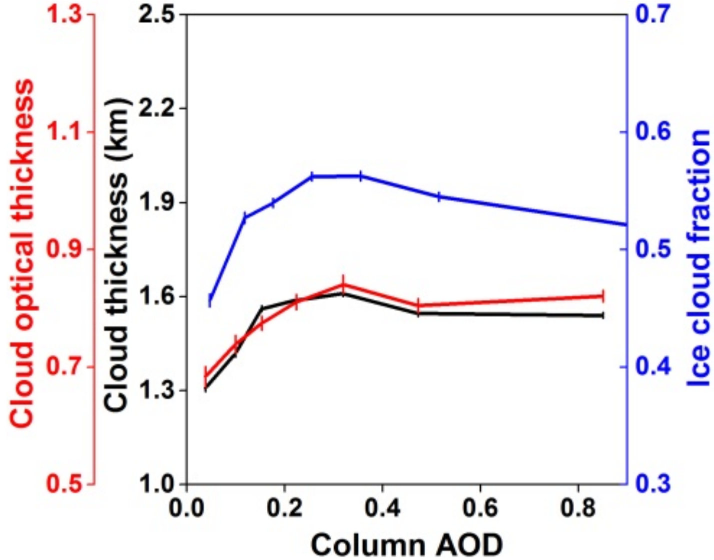


Zhao et al., 2018 GRL

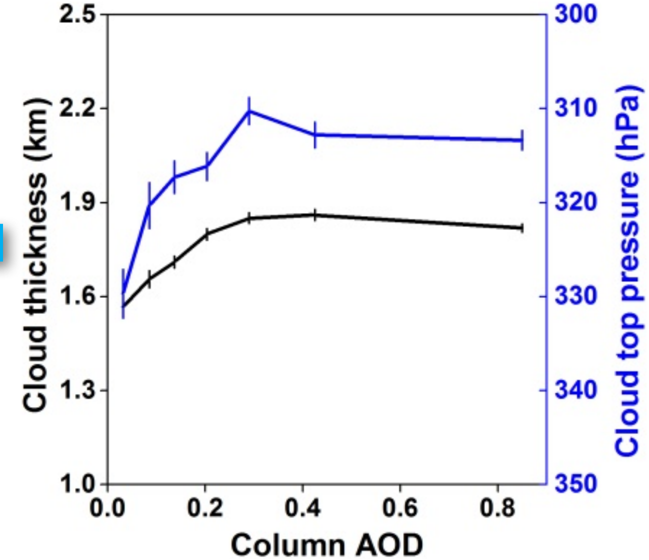
- ❑ **For convection-generated ice clouds, COT, cloud thickness, and ICF increase with small-to-moderate aerosol loadings (AOD < 0.3), and decrease with further aerosol increase.**
- ❑ **For in-situ formed ice clouds, however, these cloud properties increase monotonically and more sharply with aerosol loadings.**

Mechanisms for the aerosol impact: convection-generated ice clouds

Convection-generated ice clouds



Deep convective clouds



Small aerosol loading

Invigoration of deep convection (Rosenfeld et al., 2008)

Clouds increase with AOD

Large aerosol loading

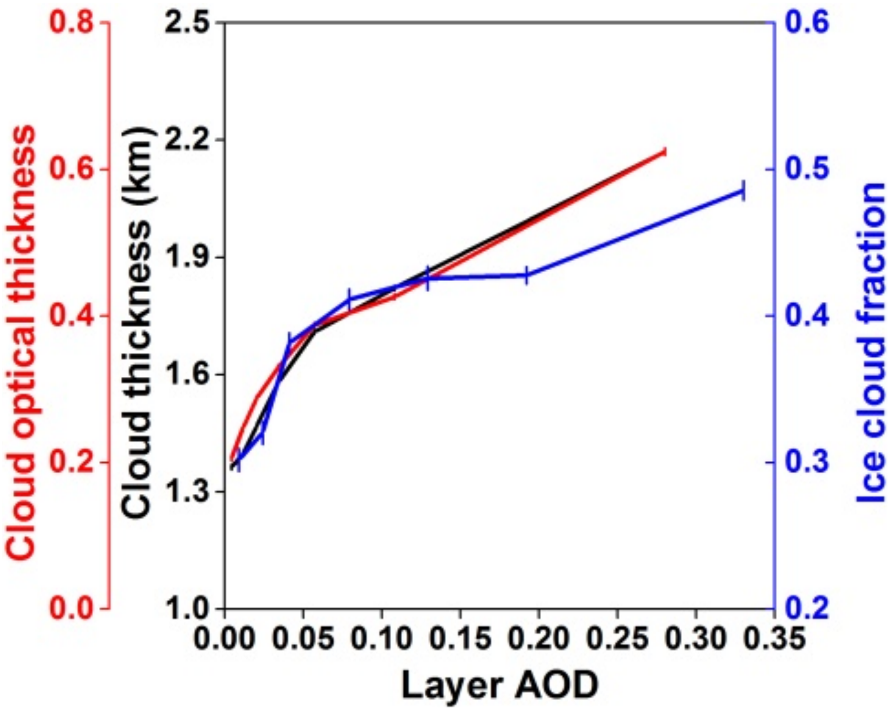
Inhibition of deep convection (Rosenfeld et al., 2008)

Evaporation due to absorptive heating (Koren et al., 2008)

Clouds decrease with AOD

Mechanisms for the aerosol impact: in-situ ice clouds

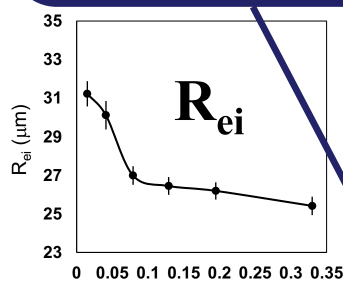
In-situ formed ice clouds



Increased aerosol loading

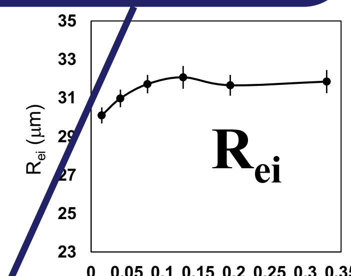
if homo dominates

More numerous and smaller ice crystals, therefore reduced sedimentation rates



if hete dominates

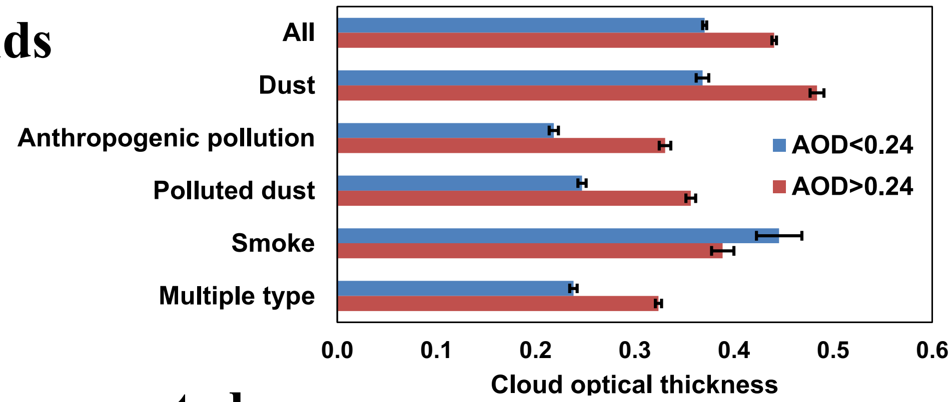
More ice crystals at similar size



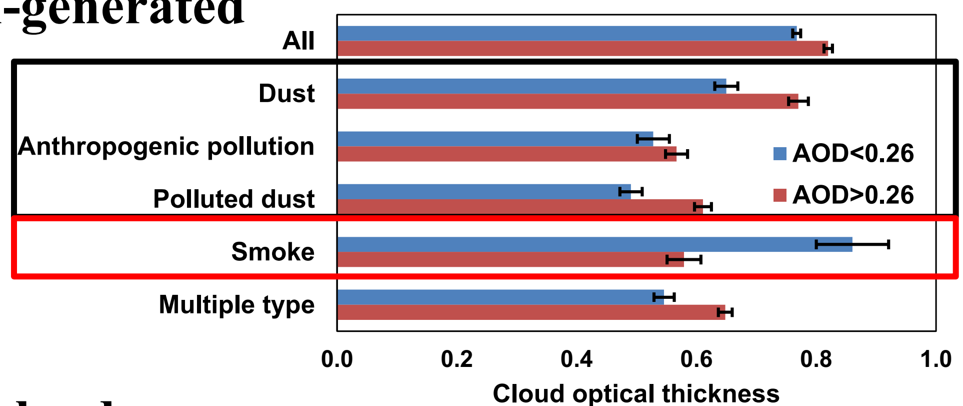
Increased ice water content

Impact of different aerosol types on COT

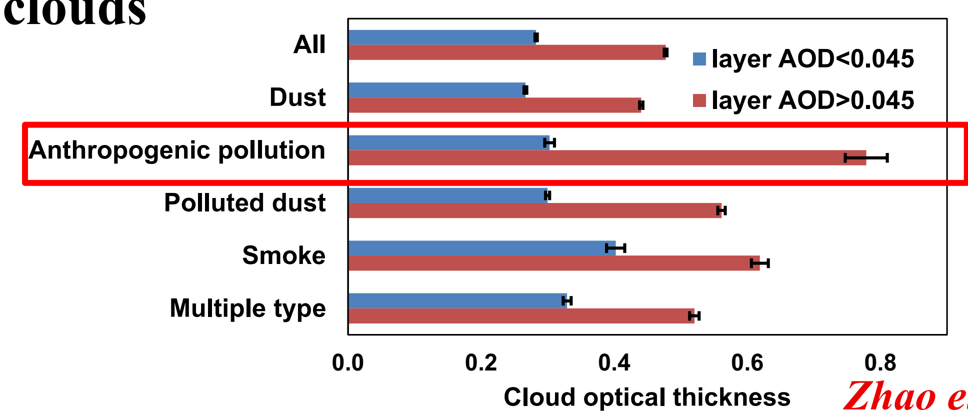
All ice clouds



Convection-generated ice clouds



In-situ ice clouds

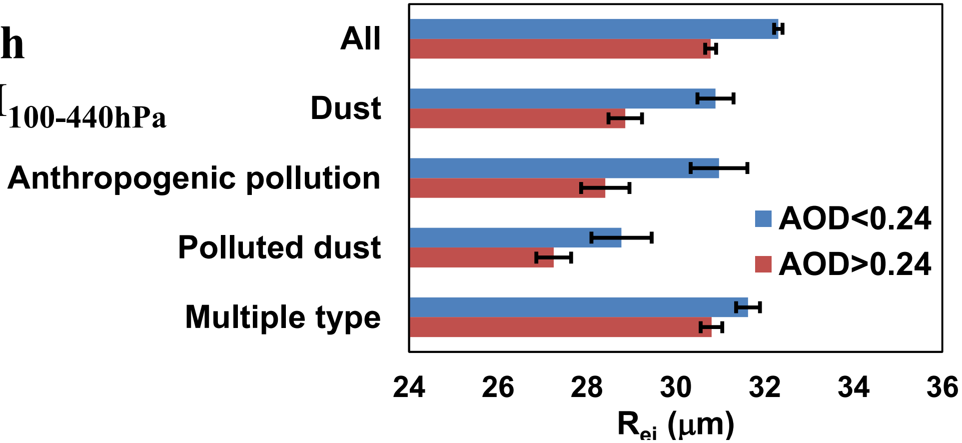


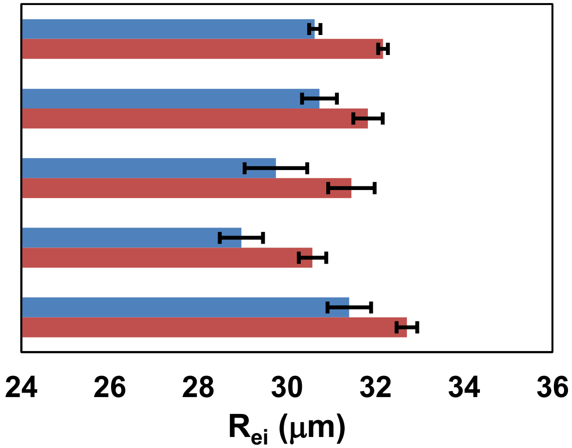
- For convection-generated ice clouds, an increase in loadings of dust and anthropogenic pollution aerosols generally enhances COT; however, an increase in smoke reduces COT.
- For in-situ ice clouds, an increase in layer AOD of any aerosol type results in significant increase in COT.

Zhao et al., 2018 GRL

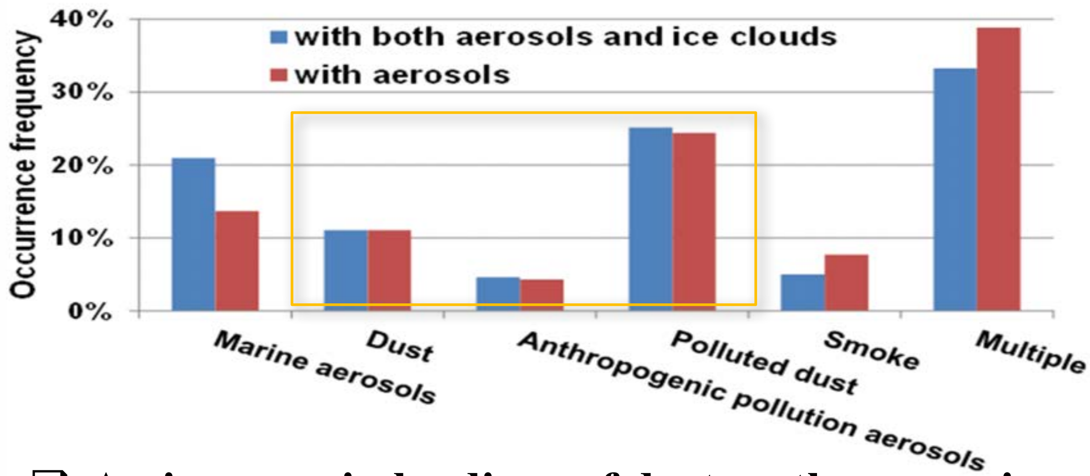
Impact of different aerosol types on R_{ei}

high $RH_{100\text{-}440hPa}$





low $RH_{100\text{-}440hPa}$



Occurrence frequencies of different aerosol types distinguished by CALIPSO. The red columns are calculated based on all profiles with valid AOD during 2007-2015, and the blue columns are calculated based on only the profiles with coexisting aerosols and single-layer ice clouds.

- An increase in loadings of dust, anthropogenic pollution aerosols, or polluted dust reduces R_{ei} under moist conditions, but enlarges R_{ei} under dry conditions.
- Considering the similar frequencies of these aerosol types coexisting with ice clouds, **it is very likely that dust and anthropogenic pollution aerosols have similar ice nucleating abilities.**

Take-home message

What's the impact of various aerosol types on the physical properties of two ice cloud types?

- Cloud fraction and optical thickness of convection-generated ice clouds increase with small-to-moderate aerosol loadings (<0.3 AOD), but decrease with further aerosol increase. For in-situ formed ice clouds, however, these cloud properties increase monotonically and more sharply with aerosol loadings.

- The responses of R_{ei} to aerosol loadings are modulated by water vapor amount: A significant negative correlation between Rei and aerosol loading in moist conditions, consistent with the "Twomey effect" for liquid clouds; A strong positive correlation between the two in dry conditions.

- An increase in loadings of dust, anthropogenic pollution aerosols, and their mixture generally enhances COT of both ice cloud types. These aerosol types also exert similar effects on R_{ei}, implying that they all contain substantial amount of INPs.

- An increase in loadings of smoke aerosols reduces COT of convection-generated ice clouds.

Acknowledgment

Thank you for your attention!

- ❑ **NASA ROSES TASNPP (Grant 80NSSC18K0985)**

References:

Zhao, B.*, Y. Gu*, K. N. Liou, Y. Wang, X. Liu, L. Huang, J. H. Jiang, and H. Su, 2018: Type-dependent responses of ice cloud properties to aerosols from satellite retrievals. Geophys. Res. Lett., 45, 3297-3306, DOI 10.1002/2018GL077261 (*corresponding author).

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